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Life cycle environmental and economic assessment of ceramic tile production: A case study in China

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ABSTRACT

Ceramic tiles are important building materials, but their production consumes large amounts of energy and raw materials and causes serious pollution. In this study, a cost combined life cycle assessment is conducted to quantify the environmental and economic impacts of ceramic tile production from cradle to gate and identify the key substances and processes to eliminate production issues. Results show that marine ecotoxicity, climate change, terrestrial ecotoxicity, human toxicity, and fossil depletion are the key environmental impact categories. Key substances include chlorine in soil, sulfur dioxide in air, and carbon dioxide in air. The total economic cost is \$2.77/m^2, and this cost mainly originates from raw materials. Inorganic chemicals used as raw materials account for general environmental (12.9%) and economic (39.6%) burdens. Application of alternative electricity generation types, such as hydropower as a replacement for coal power, can reduce the impacts on climate change and marine ecotoxicity by 98.4% and 96.4%, respectively, during the electricity generation stage. An environmental and economic win−win situation can be achieved by reducing the use of inorganic chemicals, coal, and electricity and optimizing the transport of raw materials.

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1. Introduction

Ceramic tiles are decorative building materials made from clay, feldspar, quartz, or other inorganic non-metallic raw materials that are processed through forming and sintering. These materials are shaped into plates or blocks and utilized as covering for the walls and floors of buildings or structures (ISO 13006, 2012).

All ceramic sectors are characterized as energy-intensive industries because their energy consumption accounts for 30% of the total production cost (Cerame-Unie, 2016). The pollutant composition of wastewater is complex. Solid waste (e.g., scrap, waste residue, waste mold) affects land occupation. Exhaust gas, including sulfur dioxide (SO_2), nitrogen oxides (NO_X), and dust, is mainly generated by preparation (drying tower) and firing processes (Wu et al., 2013). Thus, the government and ceramic sectors in China, which is a large producer of ceramic products, advocate for a clean production process and aim to eliminate the high levels of pollution and consumption attributed to the ceramic industry. Adjustments to the industrial structure have also been implemented to improve the conditions of production and reduce pollutant, and clean production is encouraged. The key pollution sources and processes must be determined to reduce pollutants and costs in the ceramic tile industry, and these factors require a comprehensive study.

Life cycle assessment (LCA) and life cycle costing (LCC) analysis are important environmental and economic management tools, respectively, for systematically evaluating the inputs and outputs of products, processes, or activities and their potential environmental and economic impacts on the life cycle of product systems (ISO 14040, 2006; ISO 14044, 2006). Extensive research effort has been devoted to LCA of ceramic tiles worldwide. LCA comparisons of the environmental performance of ceramic and marble tiles as flooring materials were conducted in Italy. Ceramic tiles process a worse environmental profile than marble tiles because of the raw materials utilized for glaze manufacturing (Nicoletti et al., 2002). Advanced ceramic products have been investigated along with the development trend (Breedveld et al., 2007; Pini et al., 2014; Belussi et al., 2015). For example, data from 35 Spanish enterprises were investigated in a previous work via a statistical analysis to identify

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the key stages that exert the dominant effect on the environment (Ibáñez-Forés et al., 2011). A case study evaluated the environmental performance of ceramic tiles (Bovea et al., 2010). Both studies indicated that the key considerations are tile manufacturing and energy efficiency of the firing process. In addition, the global warming potentials of five main construction materials, including ceramic tiles, were investigated in Scotland (Asif et al., 2007). The investigation revealed that ceramic tiles account for 14% of the total embodied energy of the studied house. Almeida et al. (2016) performed an environmental impact assessment of average data from four ceramic tile factories in Portugal in 2012 through a cradle-to-grave LCA methodology. The authors suggested that optimization of fuel consumption, electricity, and raw material transport distance can significantly reduce the overall environmental burden. In Sri Lanka, the amounts of carbon dioxide (CO_2) and non-hazardous wastes are significant in the drying stage and production process, respectively (Edirisinghe, 2013). When Thai ceramic tiles were assessed with the Eco-indicator 99 methodology (Tikul and Srichandr, 2010), the results showed that fossil depletion and climate change are the most affected categories. Chemicals are the major contributors in the other affected categories. Tikul (2014) compared small and medium-sized ceramic tile enterprises. Small plants, which are negative in terms of environmental management measures, consume twice the energy medium-sized plants do and exert serious environmental impacts on most categories per functional unit. Meanwhile, several relevant studies published in Chinese are available (Chen and Ma, 2008; Tang et al., 2010; Xie and Wang, 2013; Yu and Zeng, 2016), although only one LCA of ceramic tiles has been reported in an international peer-reviewed journal (Geng et al., 2017). Geng et al. (2017) compared the life cycle carbon reduction and cost benefit of wood flooring against those of ceramic tiles on the basis of a national public database and relevant literature data. Process-based on-site data are required for a precise analysis, and other categories should be assessed to avoid pollutant transfer. Moreover, sensitivity and uncertainty analyses are yet to be conducted in Chinese LCA studies. The data sources, data quality, and system boundaries of Chinese LCAs are also unclear. Huang et al. (2013) provided partial primary data on energy and material consumption. China has been the largest producer of ceramic tiles worldwide since the 1990s. Its exports ranked first at the start of the 21st century. Data show that over 45% of the world's total ceramic tiles are manufactured in China (Huang, 2015). The domestic statistical data of China show that the annual production of ceramic tiles exceeded 10 billion m^2 by 2014 (DRC, 2012, 2013; CBCSA, 2016). These statistics highlight the need to conduct LCA of ceramic tile production in China. For the LCC of ceramic tiles, only Settanni and Emblemsvåg, 2010 quantified the economic impact of the manufacturing of ceramic floor tiles. In this study, we attempt to fill this research gap by analyzing the environmental and economic impacts of ceramic tile production via a case study using LCA and LCC. The study aims to (1) quantify the environmental and economic impacts of ceramic tile production, (2) identify the key substances and processes for improvement, (3) perform an uncertainty analysis for proper LCA in decision making, (4) establish geographically specific data on Chinese ceramic tile production, and (5) provide useful information for decision makers in their effort to build and transform the ceramic tile industry from environmental and economic perspectives.

2. Scope and methods

2.1. Functional unit

The functional unit in this study was the production of 1 m^2 ceramic tile, which was the combination of a 0.4 m^2 interior wall tile and 0.6 m^2 polished tile (i.e., double loading tile) according to the production proportion in the studied factory. Such functional unit can provide a quantified reference when compared with all related product inputs and outputs (ISO 14040, 2006). Table S1 (Supplementary materials S1) shows the main characteristics of ceramic tile considered in this study.

2.2. System boundaries

Fig. 1 shows the system boundary, which is set with a cradle-to-gate approach. The commonly employed ceramic tile production flow in China was considered in this study. The flow mainly includes material preparation, pressing, glazing, firing, waxing, and individual polishing for polished tile production. Raw materials, energy consumption, road transport (assumed 100 km), direct emissions (i.e., chloride, CO_2, SO_2, NO_X, and particulates), and waste treatment (i.e., water and air control, municipal solid waste disposal to landfill, and industrial hazardous waste (i.e., tar) disposal to incineration) were considered in each process in this scenario. The traditional activated sludge method was applied for water control, that is, wastewater treatment, and bag-type dust removal and dry desulfurization were utilized for air treatment.

2.3. Inventory and data sources

The primary data (i.e., inventory of foreground system) of the scenario were obtained from a production factory located in Jiangxi Province, China. The 2014 enterprise statistical (i.e., raw materials consumption and solid waste generation) and monitoring data (i.e., direct water and air emission) were utilized. This factory, which consists of two parts, has an annual output of 3.2×10^7 m^2 ceramic tiles. One part produces interior wall tiles and, accounts for 40% (1.28×10^7 m^2) of the total production, whereas the other part produces polished tiles and accounts for 60% (1.92×10^7 m^2) of the total production. The treated wastewater was released to the river. The fuel consumed in the given scenario was self-made water gas (i.e., carbon monoxide and hydrogen mixtures), which is produced with coal and has a maximum temperature of 1200 °C. Primary data on coal consumption and monitoring data on coal's pollutant emissions are presented in Table 1. The annual average dust removal efficiency, SO_2 removal rate, and industrial water recycling rate of the target factory were 90.4%, 89.5%, and 100%, respectively. Secondary data (i.e., inventory of background system such as the inventory of limestone, coal mining, national coal-based electricity generation, road transport (assume 100 km for raw materials transportation by 40 t truck), municipal solid waste landfill and dumping, wastewater treatment, and industrial hazardous waste incineration processes) were acquired from the Chinese Process-based Life Cycle Inventory Database (CPLCID, 2016; Details in Supplementary materials S2), which is an internationally reviewed database of typical enterprises in China (Zhang et al., 2016). Considering that glaze is mainly composed of inorganic chemicals (e.g., feldspar, calcium phosphate, limestone, zinc oxide, and chromium oxide), the process of inorganic chemical production in the Ecoinvent database (Ecoinvent centre, 2015) was used for glaze production in this study to supplement the limited data in China. Relevant background data (i.e., inorganic chemicals and tap water) from Europe (Ecoinvent centre, 2015) were also utilized. To reduce the impact of the regionalized effects of applying European data and to adapt to China's condition, we used Chinese background inventory data for the process of municipal solid waste disposal to landfills, industrial hazardous waste incineration, coal power generation, coal-based steam production, and road transportation contained in CPLCID instead of the relevant process in Ecoinvent. The life cycle

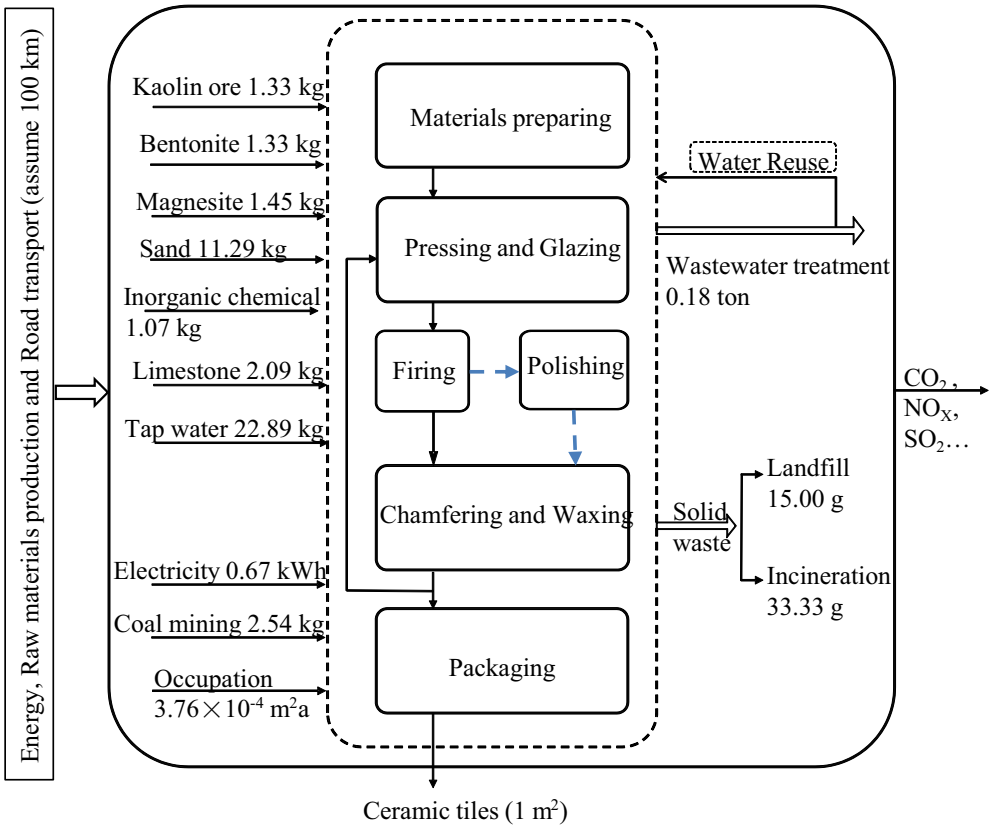

Fig. 1. System boundary of 1 m^2 ceramic tile production.

inventory results of ceramic production are presented in Table 1. All inputs and outputs are based on the functional unit.

2.4. Life-cycle impact assessment methodology

The life cycle impact assessment (LCIA) results were calculated using the ReCiPe method at the midpoint level (Goedkoop et al., 2009; Supplementary materials S3). Eighteen midpoint categories were assessed, as shown in Table 2. Normalization was applied to the latter to evaluate the different environmental indicators from an intuitive perspective on the basis of the ratio of the impact per unit of emission divided by the per capita world impact value of the year 2000 (Wegener Sleeswijk et al., 2008).

2.5. Life cycle costing

Combined environmental and economic impacts were assessed by applying LCA coupled with LCC on the basis of the investigations of Hong et al. (2012, 2015). For each process, the inventories were combined with the cost database (i.e., market price of raw materials, energy, transport, labor, construction, tax, interest, and maintenance in China) and characterization factors involved in the ReCiPe method. External market prices were considered (based on April 16, 2017, exchange rate of USD 1.00 = CNY 6.88). Table 1 presents the cost per functional unit of each input. Environmental and economic credits due to waste recycling and reuse were excluded in this study. The bank interest rate was 6.56%, and the lifespans of construction and equipment were set to 40 and 15 years, respectively. Notably, LCC analysis of the infrastructure of the ceramic tile production factory was performed, whereas LCA analysis of the same was excluded because of data limitations.

3. Results

3.1. LCIA results

Table 2 presents the LCIA midpoint results with squared geometric standard deviation (GSD^2, Supplementary materials S4) values, based on the functional unit. The LCIA medium values for 1 m^2 ceramic tile production were 14.45 kg CO_2 eq (12.46–16.76 kg CO_2 eq) on climate change, 7.96×10^{-3} kg 1,4-DB eq (5.04×10^{-3}–1.26×10^{-2} kg 1,4-DB eq) on marine ecotoxictiy, and 0.21 kg Fe eq (0.12–0.38 kg Fe eq) on metal depletion. The potential score ranges were defined by the division and multiplication results between the medium value and GSD^2 value of a category with a 95% confidence interval. Similar deductions were implemented for the other categories.

The normalized midpoint results per functional unit are displayed in Fig. 2. Two scenarios were considered: with control and without control. The scenario with control is the production process with air and water control and reflects the present case. The scenario without control is the production process without air and water control; it reflects the scenario before waste is discharged and serves as an additional scenario for comparison. Notably, the solid waste disposal approach was assumed to be the same in both scenarios, whereas air and liquid waste control approaches were assumed to be different in the considered scenarios. Most of the impacts on the environmental categories, especially freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, and marine exotoxicity, in the scenario without control were significantly higher than those in the scenario with control. In the scenario with control, climate change, human toxicity, terrestrial ecotoxicity, marine ecotoxicity, and fossil depletion were the most significant contributors to the overall environmental burden. The

Table 1
Life cycle primary inventories of ceramic tiles production. Values are presented per functional unit.

	Categories	Unit	Amount	Cost ($)
Raw materials	Kaolin ore	kg	1.33	7.92×10^{-2}
	Bentonite	kg	1.33	7.34×10^{-2}
	Magnesite	kg	1.45	4.21×10^{-2}
	Sand	kg	11.29	0.39
	Inorganic chemicals	kg	1.07	0.36
	Limestone	kg	2.09	0.14
	Tap water	kg	22.89	7.88×10^{-2}
Energy consumption	Electricity	kWh	0.67	7.59×10^{-2}
	Coal	kg	2.54	0.18
	Land occupation	m^2a	3.76×10^{-4}	–
Emissions to air	Particulates	g	1.87	–
	Fluoride	g	0.04	–
	Cadmium (Cd)	g	1.83×10^{-4}	–
	Nickel (Ni)	g	2.30×10^{-3}	–
	Chloride	g	0.14	–
	SO_2	g	2.37	–
	NO_X	g	6.19	–
	CO_2	kg	8.04	–
Emissions to water	Suspended solids (SS)	g	54.48	–
	COD	g	390.46	–
	BOD_5	g	1.05×10^2	–
	NH_3	g	21.88	–
	Sulfate	g	1.07	–
	Nitrogen	g	10.81	–
	Phosphorus	g	2.99	–
	Petroleum oil	g	0.36	–
	Nickel (Ni)	g	0.45	–
	Chromium (Cr)	g	0.13	–
	Arsenic (As)	mg	24.52	–
	Mercury (Hg)	mg	0.06	–
	Lead (Pb)	mg	9.08	–
	Cadmium (Cd)	mg	0.91	–
Waste to Treatment	Industrial hazardous waste incineration	g	33.33	1.36×10^{-2}
	Municipal solid waste to landfill	g	15.00	2.61×10^{-3}
	Wastewater	ton	0.18	2.41×10^{-2}
Labor	–	–	–	0.20
Construction	–	–	–	0.17
Equipment	–	–	–	0.46
Transport	–	–	–	0.11
Maintenance	–	–	–	0.24
Tax	–	–	–	0.21

Table 2
LCIA midpoint results of ceramic tile production. Values are presented per functional unit.

Categories	Ceramic tiles	
	values	GSD^2
Climate change	14.45 kg CO_2 eq	1.16
Metal depletion	0.21 kg Fe eq	1.80
Fossil depletion	2.19 kg oil eq	1.21
Water depletion	9.50×10^{-2} m^3	1.21
Marine ecotoxicity	7.96×10^{-3} kg 1,4-DB eq	1.58
Human toxicity	0.80 kg 1,4-DB eq	1.50
Terrestrial acidification	2.81×10^{-2} kg SO_2 eq	1.50
Terrestrial ecotoxicity	1.54×10^{-2} kg 1,4-DB eq	1.81
Particulate matter formation	1.02×10^{-2} kg PM_{10} eq	1.34
Agricultural land occupation	5.60×10^{-2} m^2a	2.55
Urban land occupation	6.92×10^{-2} m^2a	1.68
Ozone depletion	1.04×10^{-7} kg CFC-11 eq	1.67
Freshwater eutrophication	4.19×10^{-5} kg P eq	1.86
Marine eutrophication	1.02×10^{-3} kg N eq	1.25
Photochemical oxidant formation	2.48×10^{-2} kg NMVOC	1.27
Freshwater ecotoxicity	8.54×10^{-4} kg 1,4-DB eq	1.62
Ionising radiation	0.21 kBq U235 eq	2.60
Natural land transformation	8.45×10^{-4} m^2	2.73

present product exerted a minor impact on terrestrial acidification, particulate matter formation, and metal depletion. The influence on the rest of environmental categories was negligible.

3.2. Main contributors

Fig. 3 shows the main processes that contributed to the key categories. These processes were selected according to the scenario with control. Inorganic chemicals were the major contributors and accounted for over 50% in most categories. Inorganic chemicals were related to glaze, which consists of a series of mineral raw materials, such as kaolin ore and magnesite. For marine ecotoxicity and terrestrial ecotoxicity, which were the two most affected environmental categories, the related links of inorganic chemicals accounted for over 85%. Direct air emission (i.e., direct atmospheric emissions from the tile production site) and transport were the second-rank contributors. Direct air emission was the key contributor to climate change, with a proportion of 55%. It accounted for approximately a quarter of the burden on terrestrial acidification and particulate matter formation. The use of coal played a significant role in the fossil depletion category.

The most affected environmental categories that were selected according to the normalized midpoint results are presented in Fig. 4. This figure shows the specific substances that contributed to the environmental categories and their respective contribution ratios. Chlorine (Cl) in soil generated from inorganic chemical production processes provided the most significant contribution to marine ecotoxicity, terrestrial ecotoxicity, and human toxicity. SO_2 in air was the primary substance that contributed to terrestrial acidification and particulate matter formation. Nickel (Ni) in water

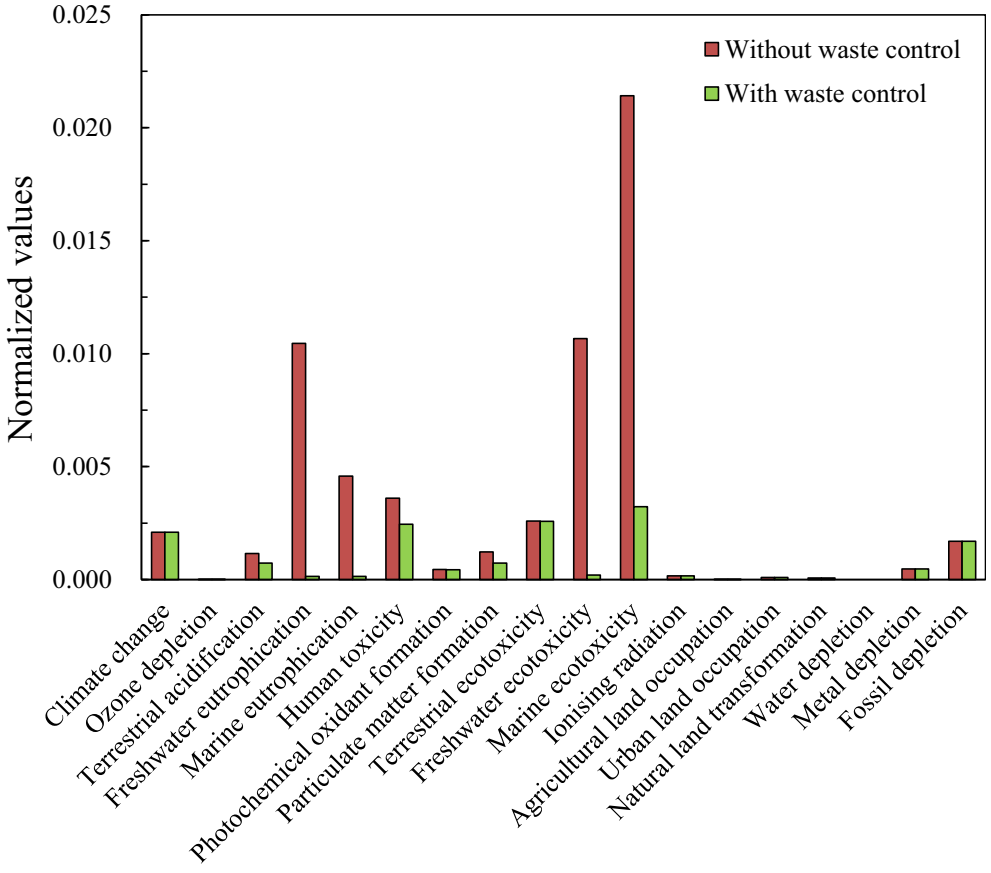

Fig. 2. Normalized midpoint results.

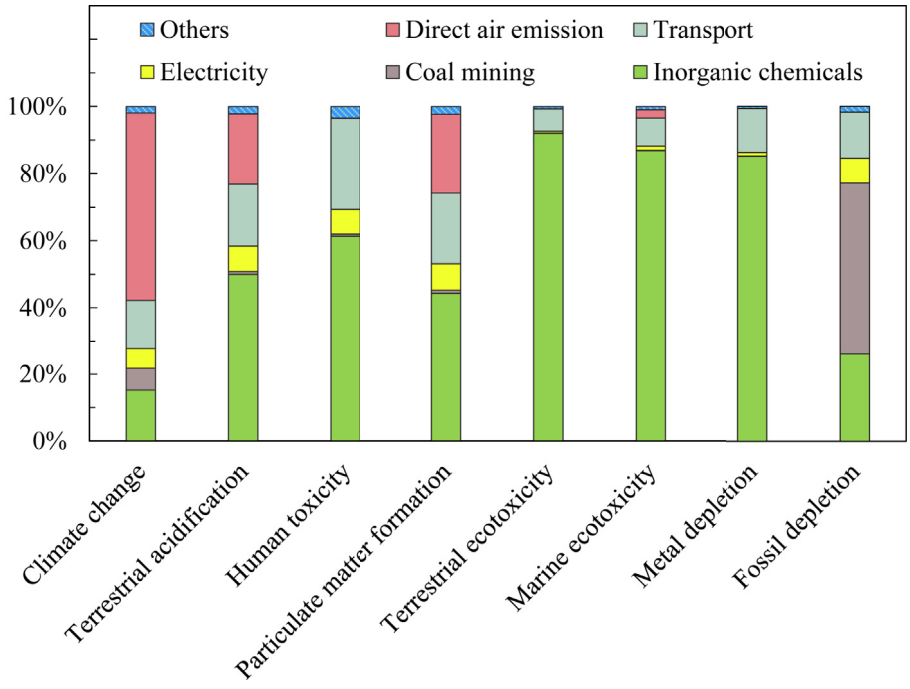

Fig. 3. Main processes that contribute to significantly affected categories.

was the dominant contaminant without pollution control for marine ecotoxicity. Most of the Ni content was removed with pollution control. The ratio of Cl to soil proportionally increased for the rest of the pollutants. Thus, Cl in soil dominated most of the environmental burden on marine ecotoxicity with control. In terms of climate change, which is a category of general concern, CO_2 in air

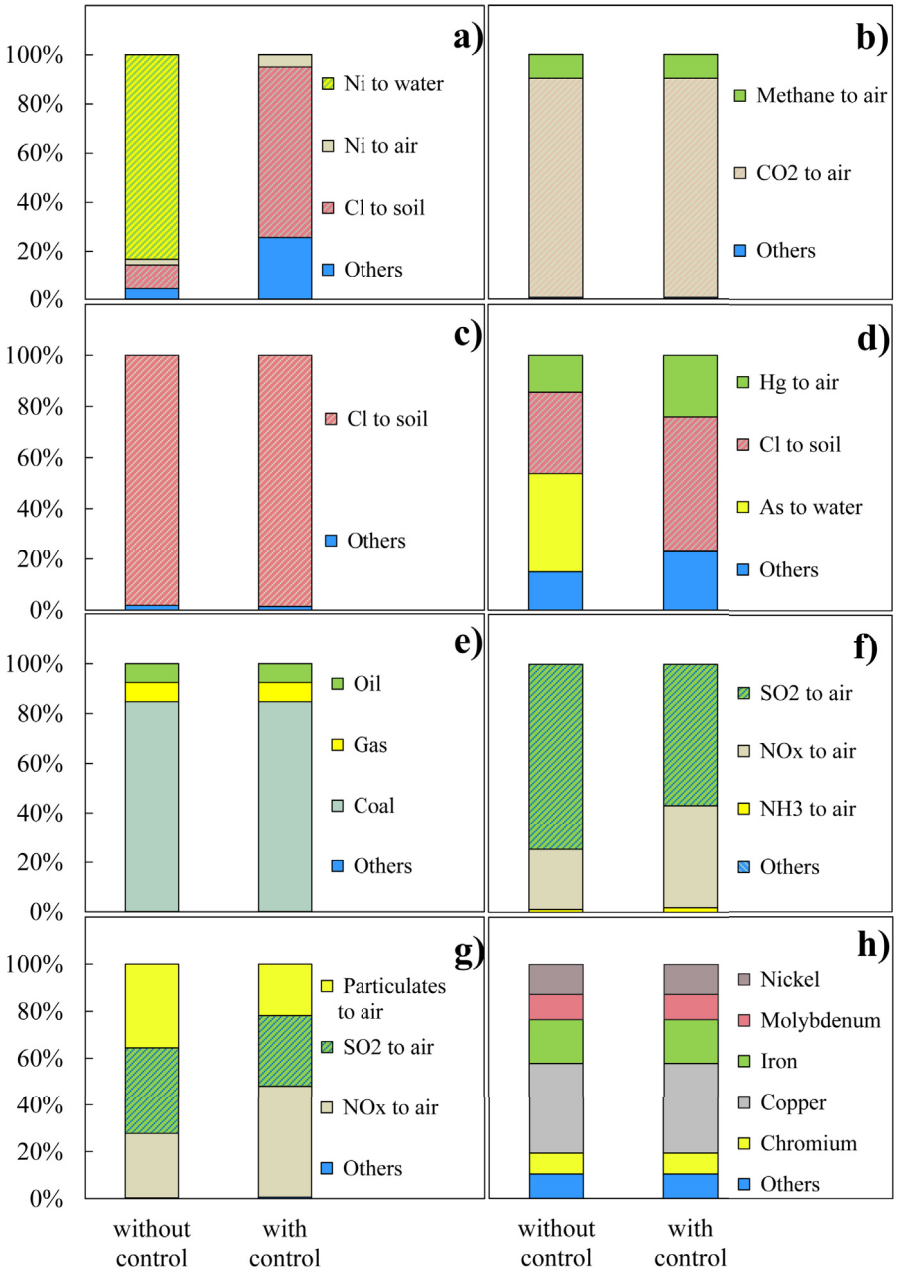

Fig. 4. Contributions of the most significant substances to key categories: a) Marine ecotoxicity; b) Climate change; c) Terrestrial ecotoxicity; d) Human toxicity; e) Fossil depletion; f) Terrestrial acidification; g) Particulate matter formation; h) Metal depletion.

was the most significant contributor in both scenarios. For terrestrial ecotoxicity, fossil depletion, and metal depletion, the results were the same in both scenarios.

3.3. Life cycle costing

Fig. 5 shows the LCC results of the scenario with control. The total economic cost was \$2.77/m^2 with a net profit of \$0.27/m^2. The main contributors that accounted for over 10% of the overall economic cost were equipment cost and the prices of sand and inorganic chemicals. Meanwhile, the prices of raw materials, including sand and inorganic chemicals, accounted for the highest proportion (Fig. 5a).

Fig. 5b presents the results of the coupled economic cost and environmental analysis. The latter was described by the normalized overall LCIA results. Inorganic chemicals exhibited the highest economic (12.93%) and environmental (39.62%) burdens. Transport, coal, and electricity also showed high economic and environmental burdens. However, direct air emission resulted in high environmental (18.78%) and low economic (0.03%) burdens. The high economic burdens of construction, labor, tax, maintenance, sand, and equipment ranged from 6.06% to 16.38%, but their environmental burdens were low (~0%).

3.4. Sensitivity analysis

A 5% variation in the processes of the dominant contribution in this scenario was conducted to obtain the sensitivity analysis

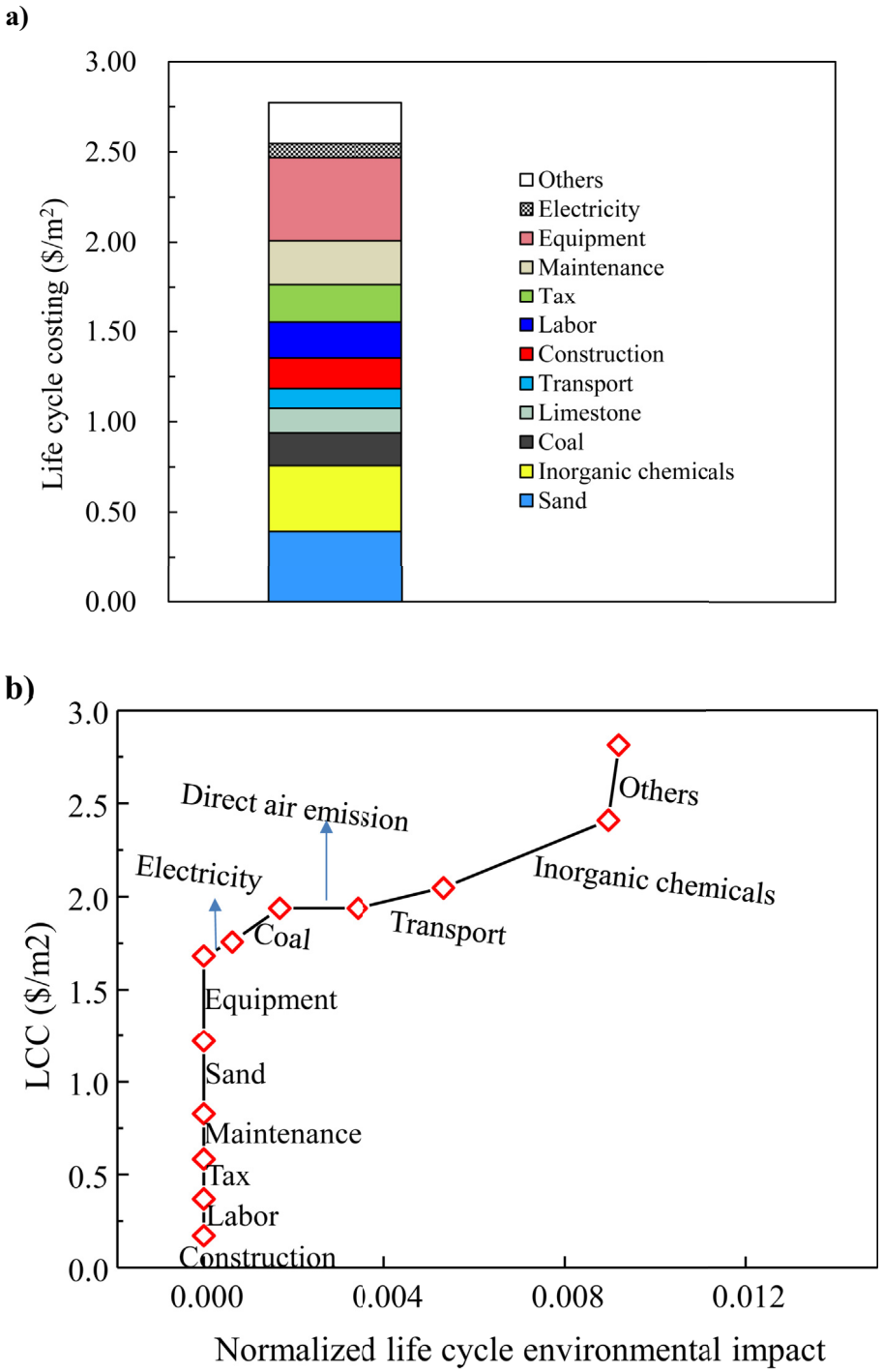

Fig. 5. LCC analysis results: a) contribution of processes; b) cost versus environmental impact.

results (Table 3). When the inorganic chemicals reduce by 5%, the climate change, marine ecotoxicity, and LCC potential score would decrease by approximately 0.11 kg CO_2 eq, 3.45×10^{-4} kg 1,4-DB eq, and1.82×10^{-2} $, respectively. For the other processes in the list, a similar deduction can be observed as shown in Table 3. Inorganic chemical variation generally resulted in the highest economic and environmental benefits in most of the affected environmental categories. The decrease in direct air emission and the increase in coal mining efficiency can significantly reduce the potential climate change and fossil depletion impacts. By contrast, coal mining had a minimally contributed to the reduction in the overall environmental impact. The reduction in direct air emission reduction presented a minimal environmental benefit to human toxicity. The variations in the efficiency of these processes did not change the source depletion for both metals and fossils.

3.5. Uncertainty analysis

Table 4 lists the probability levels determined through Monte Carlo simulation using Simapro 8.2. The probability levels were used to estimate whether the effect of the scenario without control is higher than that with control. The probability score of 100% for

Table 3
Sensitivity analysis.

	Inorganic chemicals	Coal mining	Electricity	Transport	Direct air emission	Others
Variation	5%	5%	5%	5%	5%	5%
Climate change (kg CO_2 eq)	0.11	4.72×10^{-2}	4.20×10^{-2}	0.11	0.40	1.43×10^{-2}
Terrestrial acidification (kg SO_2 eq)	7.03×10^{-4}	1.20×10^{-5}	1.06×10^{-4}	2.61×10^{-4}	2.92×10^{-4}	3.17×10^{-5}
Human toxicity (kg 1,4-DB eq)	2.45×10^{-2}	2.52×10^{-4}	2.94×10^{-3}	1.08×10^{-2}	5.04×10^{-5}	1.38×10^{-3}
Particulate matter formation (kg PM_{10} eq)	2.26×10^{-4}	4.95×10^{-6}	4.02×10^{-5}	1.08×10^{-4}	1.19×10^{-4}	1.21×10^{-5}
Terrestrial ecotoxicity (kg 1,4-DB eq)	7.07×10^{-4}	4.04×10^{-7}	4.56×10^{-6}	5.06×10^{-5}	5.90×10^{-7}	5.29×10^{-6}
Marine ecotoxicity (kg 1,4-DB eq)	3.45×10^{-4}	4.47×10^{-7}	5.06×10^{-6}	3.31×10^{-5}	1.01×10^{-5}	3.81×10^{-6}
Metal depletion (kg Fe eq)	8.92×10^{-3}	1.12×10^{-5}	1.07×10^{-4}	1.38×10^{-3}	0.00	7.87×10^{-5}
Fossil depletion (kg oil eq)	2.85×10^{-2}	5.60×10^{-2}	7.99×10^{-3}	1.51×10^{-2}	0.00	1.97×10^{-3}
LCC ($)	1.82×10^{-2}	9.04×10^{-3}	3.80×10^{-3}	5.39×10^{-3}	1.19×10^{-3}	0.10

Table 4
Uncertainty analysis results.

Categories	Probability (Without control ≥ With control)
Terrestrial acidification	100%
Marine ecotoxicity	100%
Freshwater eutrophication	100%
Marine eutrophication	100%
Particulate matter formation	100%
Freshwater ecotoxicity	100%
Human toxicity	99.3%
Climate change	56.0%
Metal depletion	50.7%
Fossil depletion	50.6%
Water depletion	50.6%
Photochemical oxidant formation	62.5%
Terrestrial ecotoxicity	52.5%
Ozone depletion	51.3%
Ionising radiation	50.6%
Agricultural land occupation	52.5%
Urban land occupation	50.7%
Natural land transformation	50.4%

terrestrial acidification indicated that the scenario without control exerted a certainly higher effect than that the scenario with control. The same analogy could also be applied to marine ecotoxicity, freshwater eutrophication, marine eutrophication, particulate matter formation, and freshwater ecotoxicity. The probability of 99.3% for human toxicity means that the effect of the scenario without control was evidently higher than that with control. The probability results for the remaining categories that scored less than 90% imply that both scenarios had similar environmental effects.

4. Discussion

Clearing the gap with advanced production levels is essential to accomplishing clean production and low emissions in the Chinese ceramic tile industry. Thus, cases of ceramic tile production in other advanced regions worldwide were utilized for comparison. The data for these cases are distributed mainly in Europe. Compared with the data used in the study of Bovea et al. (2010), the emission inventory data for the present Chinese case, excluding CO_2 emissions and hazardous solid waste (HSW), have lower emission values than the data of firms located in Castellón Province (Spain), as indicated in their annual data from 2004 to 2006, probably because the enterprise in the current study exhibits a relatively higher level of clean production than those in Bovea et al. (2010) study with a relatively old production status. Extracting the cradle-to-gate part (i.e., Stages 1–4) of the entire life cycle in the statistical analysis of Ibáñez-Forés et al. (2011) results in lower consumption or emissions of electricity, Cr, As, Hg, Pb, and HSW per m^2 than those in the present case. However, the present case generates less emissions of particulates, NO_X, and non-hazardous waste per m^2 than that in the previous study. As reported by Almeida et al. (2016), the emission inventory shown in Table 1 presents an overall lower output level than the emission inventory of Portuguese ceramic tiles, except for direct water emissions (i.e., suspended solids, BOD_5 and COD) and SO_X emissions. Chinese literature reports the life cycle inventory data of several ceramic tile manufacturing firms. Yu and Zeng (2016) reported a the life cycle carbon emission value of 0.714 kg CO_2/kg on the basis of four enterprises located in the eastern part of China. They indicated that a 1 m^2 ceramic tile with a density ranging from 15 kg/m^2 to 25 kg/m^2 generates 10.71 kg CO_2/m^2 to17.85 kg CO_2/m^2. The results obtained in this study are consistent with those of Yu and Zeng (2016) research. Under the same density range, the energy consumption of a factory ranges from 137.02 MJ/m^2 to 228.36 MJ/m^2 (Huang et al., 2013), which is much higher than that observed in the current case study (93.45 MJ/m^2).

Fig. 5b shows that inorganic chemicals (i.e., glaze), transport, and direct emissions are the key factors with the most significant environmental and economic impacts generated from ceramic tile production. The notable characteristics of the current situation of China's ceramic tile production are as follows: (1) Ceramic tile production is a regional industry that is mainly located in Guangdong, Jiangxi, Shandong, Fujian, and other provinces. (2) The northwest, northeast, and Inner Mongolian regions of China are areas rich in related resources and have small ceramic industries (Leng, 2012). A rational approach to industrial distribution is the development of backward but highly available areas and the identification of the best available distance between the locations of raw material supply and production sites. In recent years, ceramic plates, which are thinner, lighter in weight, and consume fewer raw materials than traditional ceramic tiles (Pini et al., 2014), have been promoted by the government (SAC, 2015; NDRC, 2013). Thus, the environmental and economic impacts of transport can decrease with the reduction in raw material usage. Controlling the generation of extra glaze from the source, and reusing extra glaze in strict and reasonable arrangements are also recommended.

Extra glaze and other solid waste generated in ceramic tile production processes (i.e., waste products, polishing waste, and waste plasters), are commonly treated via landfilling or simple open-air piling. However, these strategies occupy much land and are only effective in the short term. Non-renewable mineral resources are overexploited because of the large consumption of raw materials. Therefore, waste recycling must be immediately implemented. However, waste management in ceramic enterprises is basically in a blank state because of the high cost of secondary use and limitations of technical conditions (Tan et al., 2011). To date, only several large-scale ceramic enterprises in Guangdong Province, China, have attempted to recycle polishing waste by employing different methods, such as mixing the polishing waste with adobe and transforming it into lightweight bricks (Li, 2014;

Xu, 2016). The recycling of ceramic tile waste should be improved, and technical and financial support are necessary.

Given that small workshop-style manufacturing enterprises account for a large proportion of the ceramic tile industry in China, small-scale factories are generally constructed without waste treatment equipment (e.g., desulfurization for SO_2 control, dedust for particulates control, wastewater treatment). The results of the evaluation of the scenarios without and with waste treatment (air control and wastewater treatment) in freshwater eutrophication, marine eutrophication, and freshwater ecotoxicity showed that the impacts decreased by 98.6%, 97.0%, and 98.1%, respectively. Wastewater treatment and air control attained 84.9% reduction in marine ecotoxicity. Other clear decrements occurred in terrestrial acidification, human toxicity, particulate matter formation. These reductions in environmental impacts can be attributed to the removal of emissions generated by inorganic chemicals (i.e., glaze). Given the key substances identified in Fig. 4, Ni to water, which is mainly generated by glaze, was originally the dominant pollutant for marine ecotoxicity. This substance was significantly removed after wastewater control (Fig. 4a). However, inorganic chemicals are still the key process with the most significant impact on the environment after waste air and water control.

Coal-based electricity generation, which accounts for the majority of the thermal power in China, was the only type of power generation considered in the present study. The State Grid of China is a mixed power supply network, where hydropower takes a secondary share of electricity generation (DRC, 2014). Specifically, thermal, hydro, wind, nuclear, solar, and other power (e.g., biomass, geothermal) contributed approximately 73.3%, 17.0%, 2.9%, 2.4%, 0.4%, and 4.0% to the national electricity generated in 2014 (DRC, 2014). Therefore, coal-based electricity generation in the present assessment was replaced by hydropower and mixed power to investigate how the environmental impact would change based on the functional unit. The environmental impacts on most categories improved by approximately 20% during mixed power replacement; these categories included the key categories, such as climate change, human toxicity, particulate matter formation, and marine ecotoxicity. General improvements were noted in all of the environmental categories for hydropower replacement. Most of these categories significantly changed, except for ozone depletion. For climate change, human toxicity, particulate matter formation, terrestrial ecotoxicity, and marine ecotoxicity, which are the categories with utmost concern and importance, the potential scores generated from electricity decreased by 98.4%, 99.0%, 94.3%, 98.8%, and 96.4%, respectively (Supplementary materials S5). Hydropower had more environmental benefits than coal-based and mixed power generation. Hence, the development of a large proportion of hydropower and appropriate adjustment of the power structure can be an effective approach to reduce emissions and the impacts on certain environmental categories.

5. Conclusions

This study applied LCA coupled with LCC to quantify the environmental and economic impacts of ceramic tile production. The comparison results showed that waste control eliminated most emissions and correspondingly presented decreased impacts on most environmental categories. The key categories affected were marine ecotoxicity, climate change, terrestrial ecotoxicity, human toxicity, and fossil depletion. Cl in soil, SO_2 in air, and CO_2 in air were the key substances that contributed to the environmental burdens in the scenario with waste air and water control. The total economic cost was \$2.77/m^2 with a net profit of \$0.27/m^2, and this cost mainly originated from raw materials. The process-based analysis indicated that the primary process responsible for environmental and economic burdens was inorganic chemicals as raw materials, which accounted for 12.9% and 39.6% of the total burdens, respectively. The pollutants generated by inorganic chemicals were removed in large proportions through waste air and water control. Thus, the environmental impacts on half of the categories decreased according to the uncertainty analysis. Specifically, certain reductions were observed in several key categories, such as marine ecotoxicity, terrestrial acidification, and particulate matter formation. The key to reducing environmental and economic impacts is to control the process of inorganic chemical production by optimizing the transport plan and reducing the use of glaze. Optimizing the electricity structure is also recommended, given that the replacement of coal power by hydropower presented a considerable environmental advantage.

This work merely presented an analysis of a case of ceramic tile production on the basis of information on China's actual transportation and raw material distributions. However, the findings could benefit research aimed at understanding key improvements from environmental and economic perspectives. Additional studies on LCA and LCC of ceramic tile production are still necessary to further improve the representativeness of inventories.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.04.112.

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